CHARGED-PION LIFETIME AND A LIMIT ON A FUNDAMENTAL LENGTH*†

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The lifetime of the charged pion has been determined in flight. The agreement of our result, 26.02 ± 0.04 nsec, with experiments of comparable precision made with pions at rest provides the most precise verification of time dilation. In the model of Lundberg and Rédei this comparison sets an upper limit on a fundamental length of 3×10^{-15} cm. Using the measurements of velocity and momentum for both π^+ and π^-, we also obtain $m(\pi^+)/m(\pi^-) = 1.0002 \pm 0.0005$.

Previous precise measurements of the charged-pion lifetime have been made by stopping π^+ in a scintillator and observing decays at rest. The experiment reported here is by far the most accurate measurement using pions in flight[1-4] and has the same precision as the best experiments with stopping pions. Comparison of the lifetimes of particles in these two states of motion tests special relativity. In a particular model[5] this comparison sets a limit on the existence of a fundamental length.

In this experiment, performed at the Lawrence Radiation Laboratory's 184-in. cyclotron, the fraction of surviving pions was measured along a beam which alternately consisted of positive and negative particles. This attenuation as a function of distance determined both the ratio of the π^+ and π^- lifetimes and the absolute lifetime. The experimental arrangement and the ratio analysis (which does not depend strongly on the value of the lifetime) have been reported,[6] and therefore the emphasis here will be on those features which pertain only to the absolute lifetime.

A monitor counter system determined the number of momentum-analyzed pions at the start of the decay path, and a movable detector measured the number surviving at seven different positions about 6 ft apart along that path. The movable detector *CP* was a differential Cherenkov counter which used as a radiating medium either liquid hydrogen (for the absolute-lifetime measurement) or deuterium (for the lifetime ratio).[7] The monitor system included a similar differential Cherenkov counter *CM*, tuned to count pions, and, in addition, a threshold Cherenkov counter *AE* which vetoed electrons in the beam. The last counters of the monitor telescope were a series of thick scintillators with holes in the centers. These were in anticoincidence, requiring all particles in the monitor to pass through the holes, and were designed so that *CP* would intercept the entire pion beam at all of its positions. The beam traveled in vacuum along the entire decay path.

In the absence of systematic errors, the ratio R of counts in *CP* to monitor counts would vary with the distance x along the beam line according to

$$R = A \exp(-Bx). \tag{1}$$

The parameter B determines the proper lifetime τ_0 since

$$B = 1/\eta c \tau_0, \tag{2}$$

where $\eta = \beta(1-\beta^2)^{-1/2}[\equiv \beta\gamma]$. Three systematic errors could affect this analysis, however: (1) loss of beam outside *CP*, (2) imperfect rejection of decay muons by *CP*, and (3) dependence of the *CP* efficiency on the counting rate. We will now discuss these in order.

Three tests confirmed that at the first six positions of the movable counter the pion beam was well confined within its aperture. At the seventh position about 0.2 % of the beam was lost, and hence data from this position were not used in calculating the lifetime. In the first check, the cross section of the beam at each position was studied with a wire spark chamber; in the second, R was found to be unchanged when *CP* was moved a small distance perpendicular to the beam line at each position, thus the counter aperture was always larger than the beam; and in the third, the lifetime was calculated omitting either the first one or two data positions of the six, or the last one or two positions. The agreement within statistical errors among the different values indicates that there was negligible beam loss at the first six positions.

The second systematic error resulted from imperfect rejection by *CP* of muons from the decay of pions after the monitor telescope. (In contrast, the small fraction of momentum-analyzed muons and electrons which counted in *CP* caused negligible error, because the former were efficiently vetoed by *CM* and the latter by both *CM* and *AE*.) The ratio of decay muons to pions entering *CP* was about 0.06, and roughly 10 % of these muons were counted as pions. These counts would have caused no error in the calculated lifetime, however, if at every data position the same fraction of counts was due to decay muons. Because the number of pion decays a given distance ahead of the counter was proportional to the number of pions there, this fraction was almost constant. At the two most upstream data positons, however, some of the decay muons which entered *CP* were vetoed by the final anti counters. The correction for the effect of decay muons reduced the calculated lifetime by 0.032 ± 0.015 nsec. The error is primarily due to the uncertainty in the efficiency with which these particles were detected.

The third systematic error resulted from a slight rate dependence of the *CP* photomultiplier gain which made the counter efficiency a few tenths percent lower at the end of the decay path than at the start. An accurate correction for this effect could be made when liquid hydrogen was the radiating medium in *CP* because, for a given decrease in photomultipler gain, the ratio of the decreases in the π^+ and π^- efficiencies was known. To understand this point, consider what happened to pions as they entered the liquid hydrogen. Those that passed all the way through the radiator gave off a fixed amount of Cherenkov light, but those that interacted in the hydrogen produced usable light only up to the point of interaction. Thus, although most pulses from the *CP* photomultiplier were well above threshold, the presence of low-amplitude pulses (from interacting pions) made the efficiency depend on the discrimination level. Since the pion momentum (312 MeV/c) was near the peak of the $I = \frac{3}{2}$, $J = \frac{3}{2}$ pion-nucleon resonance, there were about three times as many π^+ interactions as π^-. Thus the π^+ pulse-height spectrum had more pulses near the discrimination level than did the π^-, and any change in gain affected the π^+ efficiency more than the π^-. Using the measured pulse-height spectra for plus and minus, we determined that the ratio of the changes in efficiency, for the same change in gain, was 2.4. This factor r was then used in a single least-squares fit of the observed values of R for π^+ and π^- by

$$R_- = A_- \exp(-Bx)[1 - Cf(x)] \quad (3)$$

$$R_+ = A_+ \exp(-Bx)[1 - Cf(x)] \quad (4)$$

to determine the free parameters A_+, A_-, B, and C. The lifetime is still related to B by Eq. (2). The equality of the π^+ and π^- lifetimes, which is utilized in Eqs. (3) and (4), is expected from *CPT* invariance and has been established experimentally[6] to an accuracy of 0.07 %. The term in brackets expresses the dependence of the counter efficiency on distance along the decay path. The form used for $f(x)$ was not critical because the rate dependence of the efficiency was small, and the rate varied by only a factor of two over the decay path.

In the run from which the lifetime has been determined, data of roughly the same statistical accuracy were taken at each of the seven counter positions at two different times. The fit for the 331 measurements of R at the first six positions gave a χ^2 of 316 and determined τ_0 with a statistical error of 0.031 nsec. The fit to an exponential is very good, as can be seen in Fig. 1, which shows the differences between the values of R given by the fit of Eq. (3) and the observed values. The reproducibility of pairs of measurements, taken typically two days apart, demonstrates the time stability of our system.

Having found B from R, we determined τ_0 by finding η from a time-of-flight measurement of the pion velocity, using two small scintillation counters added to the beam setup. Because of the small angular divergence of the beam, a long flight path was possible, giving a pion transit

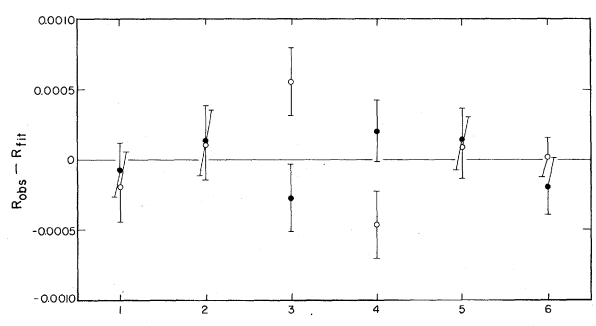

FIG. 1. Differences between the observed and fitted values of R for π^-. The closed circles are the first measurement; the open circles, the second.

time of 97 nsec. Instead of using this transit time directly, we measured the difference between the pion flight time and that of electrons (which travel essentially at the velocity of light) in the beam. This procedure had two advantages: (1) systematic error caused by small timing shifts in the electronics was avoided; and (2) for the same relative error in the measured time interval, the precision in η is better by a factor of $\gamma^2(1+\beta)\approx 11$ if the difference between the electron and pion flight times, rather than the total pion flight time, is used. This relation can be seen from

$$\frac{\delta\eta}{\eta}=\gamma^2\frac{\delta\beta}{\beta}=\frac{1}{1+\beta}\frac{\delta T}{T},$$

where T is the electron-pion time difference.

The time-of-flight spectrum for one of the 18 runs is shown in Fig. 2. Mean positions for each peak were found by curve fitting. The mean value of T was determined with a relative error of 0.16%, resulting from the fluctuations among the individual measurements as well as systematic errors from nonlinearity of the system and from the calibration procedure.[8] The corresponding error in η was then 0.09%. The derived value of η was corrected for energy loss in the upstream time-of-flight counter, which was not present during normal data taking. The equivalent total error in τ_0, including the uncertainty in the energy-loss correction, was 0.026 nsec.

The momentum of the beam was determined to 0.06% using a magnetic spectrometer with four wire spark chambers. The measured momentum and the known value of the pion mass provided a check on the time-of-flight determination of η; the values found by the two methods were in good agreement. Because momentum and η were measured for both π^+ and π^-, and the plus-minus differences were free of many systematic errors that affect the absolute values, an accurate comparison of the π^+ and π^- masses was possible. We find $m(\pi^+)/m(\pi^-)=1.0002\pm0.0005$. The best other determination of this ratio, 1.0002 ± 0.0004, was a result of independent measurements of the two masses[9,10] instead of a direct difference measurement.

The principal result of the experiment is 26.02 $\pm$0.04 nsec for the pion lifetime. The two most accurate measurements of the lifetime at rest have a comparable precision. Our lifetime has the identical value and error as one of these determinations[11] and is in good agreement with the other, 26.04 ± 0.05 nsec.[12]

Our calculation of τ_0 assumed that the lifetime in the laboratory frame was $\tau=\gamma\tau_0$; γ was ≈ 2.4. Viewed another way, the agreement between our value of τ for pions in flight and the other measurements of τ_0 for pions at rest provides the best verification of time dilation.[13] The observed change in the lifetime, $\tau-\tau_0$, agrees with the predicted value, $(\gamma-1)\tau_0$, to 0.4%.

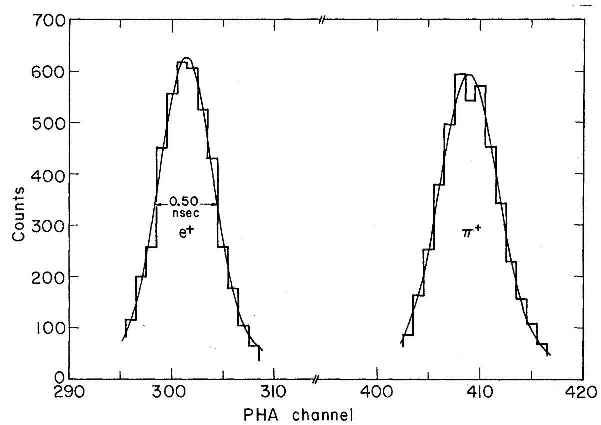

FIG. 2. Typical time-of-flight spectrum. Each fitted curve is a Gaussian plus constant background.

Lundberg and Rédei[5] have calculated the expected velocity dependence of the pion lifetime for a model in which relativity is violated at small distances. Simultaneous interaction of events having a spatial separation less than some fundamental length α was assumed. The Hamiltonian for pion decay via an $N\bar{N}$ intermediate state was modified by a form factor describing the violation of casuality. On this basis the lifetime measured in the laboratory for pions of momentum p was calculated to be $\gamma\tau_0[1+(\alpha p/\hbar)^2/5]$. Using our result with that of Ref. 11, we find $\alpha < 3\times10^{-15}$ cm. This is the first test reported for the type of relativity violation originally suggested by Blokhintsev.[14] A limit based on forward dispersion relations has recently been presented.[15]

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CHARGE AND SPIN SUSCEPTIBILITY OF A FERROMAGNETIC ELECTRON GAS. D. J. Kim, H. C. Praddaude, and Brian B. Schwartz [Phys. Rev. Letters 23, 419 (1969)].

The formulas for the susceptibility, Eqs. (3), that we have used to consider the spin and charge polarization around impurities in magnetic systems have also been obtained by Rajagopal *et al.*[1] We thank Dr. Rajagopal for calling our attention to this reference.

In addition, there are misprints in Eq. (2a) which should read "$\mathcal{H}_m' = -\mu_B H(q)\sum_l \cdots$," and Eq. (4) which should read

$$\langle a^\dagger b\rangle = -(1/2\pi i) \times \int_{-\infty}^{\infty} d\omega \{\langle b|a^\dagger\rangle_{\omega+i0^+} - \langle b|a^\dagger\rangle_{\omega-i0^-}\} f(\omega).$$

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POLARON CYCLOTRON RESONANCE IN CdTe. Jerry Waldman, David M. Larsen, Peter E. Tannenwald, C. C. Bradley, Daniel R. Cohn, and Benjamin Lax [Phys. Rev. Letters 23, 1033 (1969)].

(1) The legend over the rightmost column of numbers in Table I should read "$\alpha = 0.4$."
(2) The expression following "by" in the third line above Eq. (6) should read "$2(\hbar\omega_c)^2$."

INVESTIGATION OF BAND-MIXING ANOMALIES IN Sm^{152}. I. A. Fraser, J. S. Greenberg, S. H. Sie, R. G. Stokstad, G. A. Burginyon, and D. A. Bromley [Phys. Rev. Letters 23, 1047 (1969)].

In Table I, column 3, the uncertainties in the quoted $B(E2; 4_\gamma \to 2)$ and $B(E2; 4_\gamma \to 4)$ should read ± 0.13 and ± 1.3, respectively.